Status of the ICARUS detector and early physics programs (final)

PAC Meeting 8 Dec. 2020

ICARUS Collaboration at SBN

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1. ICARUS detector technical status - *C. Montanari*

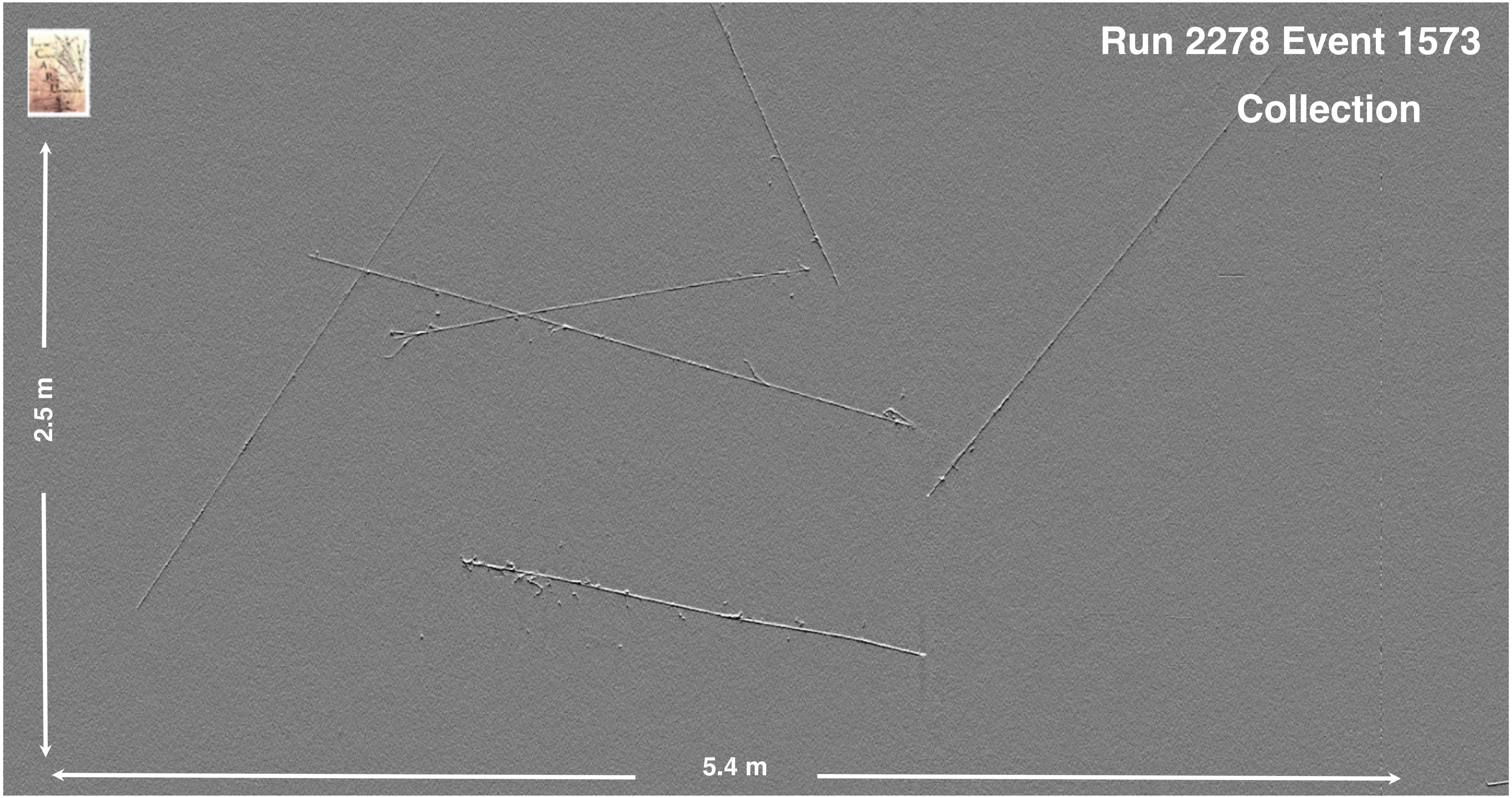
- All TPC and PMT components have been installed, cabled and commissioned with the only exception of trigger system. Most recent installation activities are:
  - DAQ fibers connections;
  - HV for the TPC drift installation;
  - Wire bias connections;
  - Cabling and dressing of trigger racks.
- The detector to building ground shorts have been found and resolved.
- All systems have passed the Fermilab Operational Readiness Clearance and can be operated continuously.
- The cryogenic system is operating in a steady state condition since June with the only exception of South Gas Argon re-circulation unit of East module still operating erratically.
- Interventions are in progress on the GAr re-condenser to achieve full functionality.
- Side CRT installation is progressing: North, West, East sides are installed/commissioned. South side installation is in progress.

ICARUS detector activation

- August 27th TPC wire planes and cathode HV were taken to nominal voltages.
  - HV has remained stable at -75 kV, without any glitches or issues. No significant currents found on the wires bias with the exception of a group of Induction-2 wires of West module that remain at 0 V (instead of -30 V).
- All PMTs were switched on (3 out of 360 not working), calibrated with laser.
- Cosmic-ray interaction events are regularly collected with a random 5 Hz trigger and data are being analyzed for calibration purposes (ex. electron lifetime, space charge, drift velocity measurements).
- Dedicated runs are also taken for specific commissioning tasks (investigation of TPC noise, PMT calibration with laser, DAQ upgrades/longevity tests, etc).
- A relatively short e-lifetime $t \approx 1$ ms is measured in both modules to be compared with 1 ms maximum e-drift time and the required $t > 3$ ms (0.1 ppb O_2 equiv.) goal.
- After some investigations it was concluded that the limited e-lifetime is most likely due to saturation of gas recirculation filters. These filters have a small capacity, due to their size and operation at LAr temperature, where the copper adsorption capacity is ~10 times smaller than at room temperature. GAr filters are being regenerated and new warm filters constructed to be installed on the gas collector lines to significantly increase the filtering capacity.
- 24/7 shifts since February 14th.
  Remote only shifts, with online control and monitoring, since March 17th

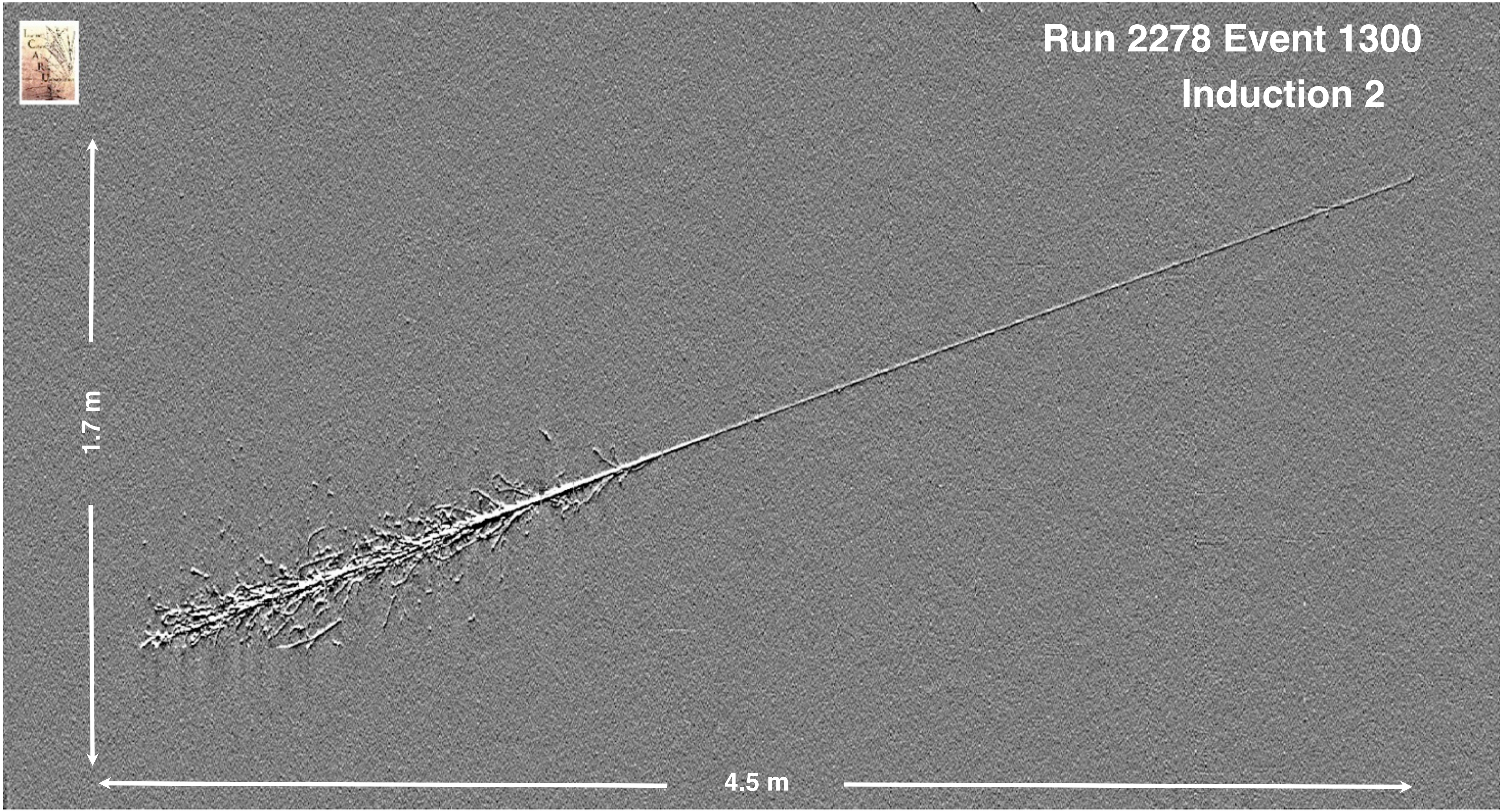
Sample events @ 500 V / cm

Recorded drift time (1.6 ms)

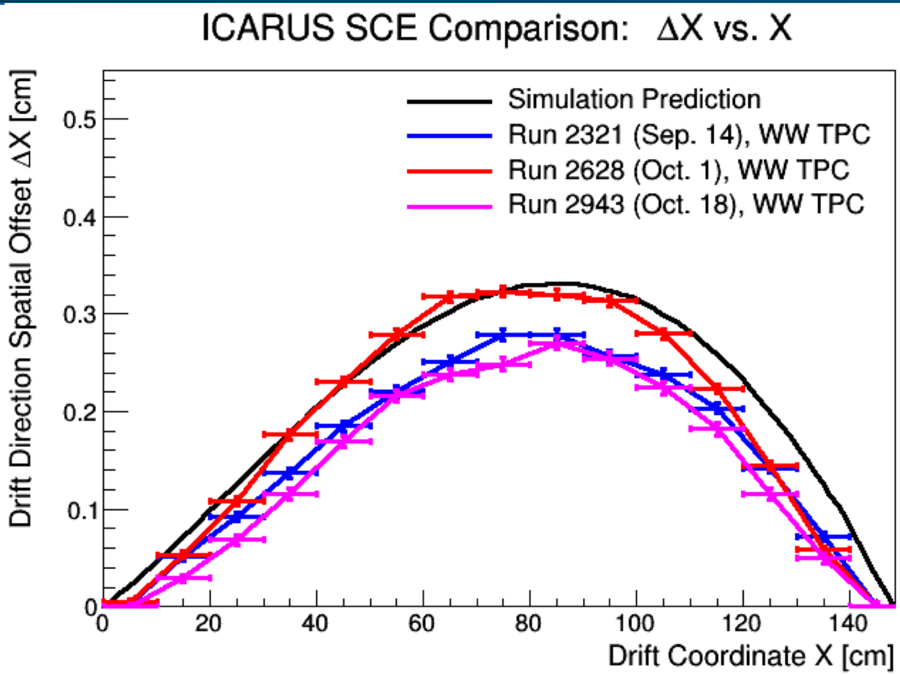


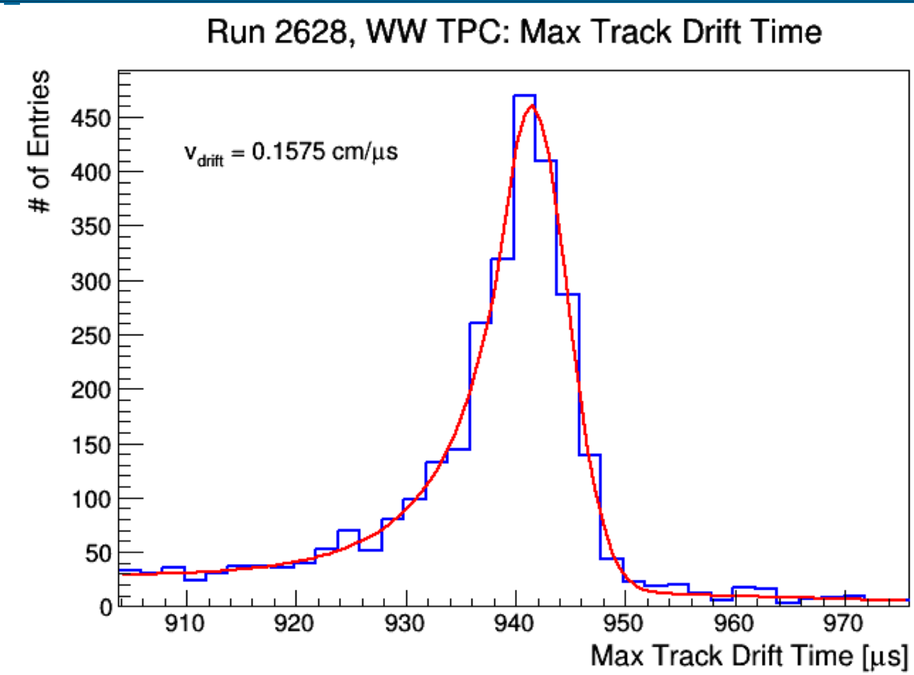
Sample events @ 500 V / cm

Recorded drift time (1.1 ms)



Space charge and drift velocity measurements



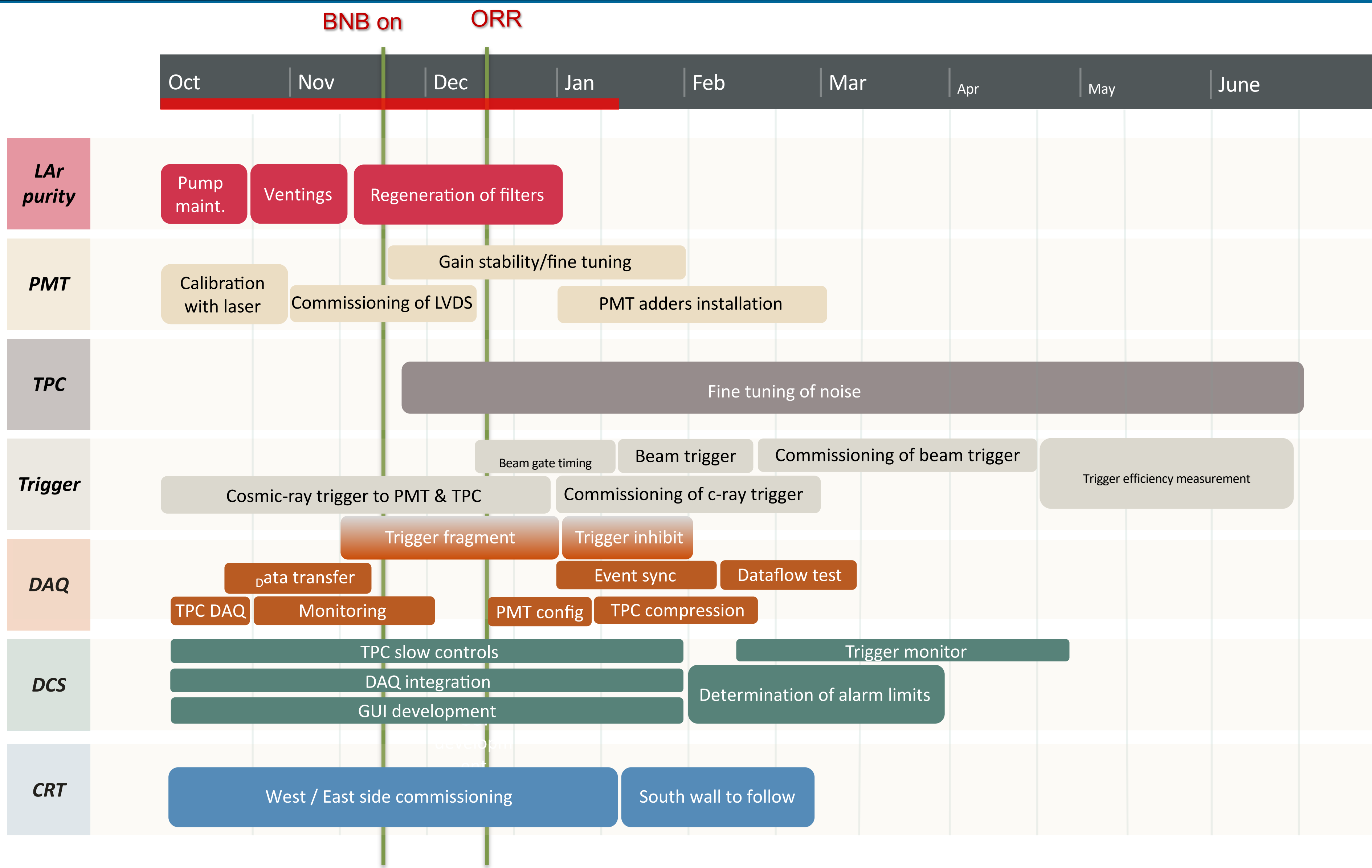


- Space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks, looking at spatial distortions in drift direction:
  - First results show rough agreement with previous ICARUS measurement (JINST 15 (2020) 07, P07001 also at https://arxiv.org/abs/2001.08934) and simulation aside from small time dependence.
- Same track sample used to measure drift velocity by estimating maximum drift time of charge associated with tracks:
  - Results in line with previous ICARUS measurements to 1-2%; small discrepancies being investigated.

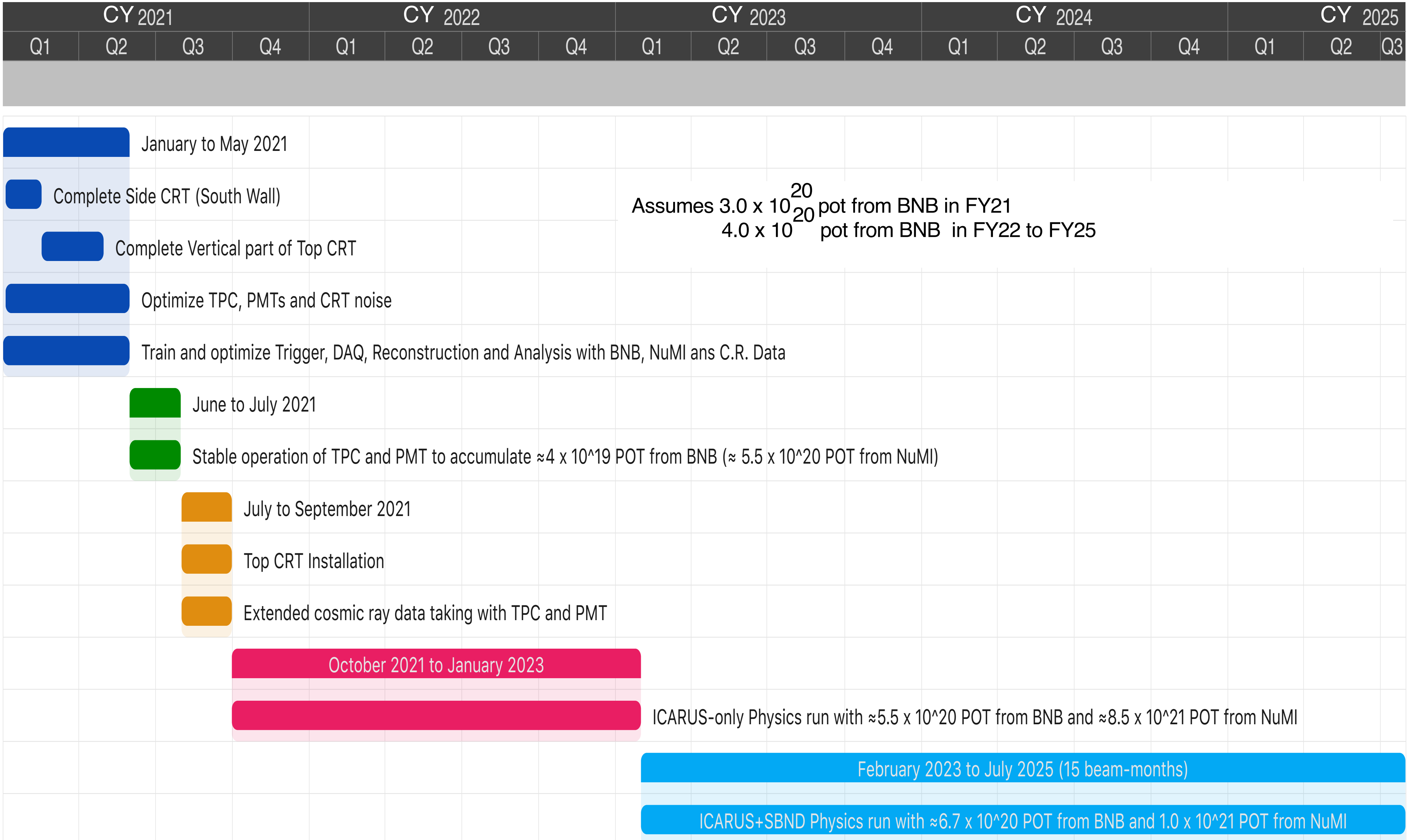
Transition to commissioning and operations

- The ICARUS installation activities are coming to a conclusion with only the trigger system to be completed and top CRT remaining to be installed. The commissioning activities are proceeding very well to be concluded when steady conditions for data taking are reached.
- The weekly meetings of the joint Technical Working Groups, overviewing the installation activities, will be progressively reduced, to be replaced by the Detector Commissioning and Operation Meetings.
- The Technical Board will continue to meet, ~ every month, to overview the remaining installation activities and ensure the continuity of the detector operation: organization of regular maintenance, broken or defective components substitution, hardware issues, organization of possible upgrades.
- The role of the Run Coordinator has been defined. The first Run Coordinator will be appointed soon, while we transition to operation.
- It is clear that data collected without the top CRT and overburden cannot be accounted in the data budget for sterile neutrino search. They will be however of extreme value for refining the trigger logic and the data analysis strategy, and for measurements not directly associated with the sterile n search.
- In parallel with the present PAC meeting, the Operation Readiness Review is taking place.

High-level planning of commissioning activities



ICARUS Run plan from FY21 to FY25



2. ICARUS data taking – *C. Rubbia*

- The operations of the Fermilab accelerator complex will most likely be resumed by about the end of this year.
- Notwithstanding, more than one half of ICARUS participants (76 people out of 140) cannot presently access the US. This situation may persist for an indefinite period of time.
- The future of the ICARUS detector at Fermilab will have to take into account these inevitable consequences both during the completion of the preparatory phase and the subsequent years of foreseen data taking.
- The detector is expected to initiate data taking shortly after the beginning of 2021, at two surface locations.

  (1) about 600 m from the Booster Neutrino beam and

  (2) off-axis of the NUMI higher energy beam.
- After the first year, it will be operated jointly with the similar LAr detector SBND at 110 meters from the Booster target (1).

Early physics programs with ICARUS

- A number of persistent neutrino related anomalies have been already recorded during several decades. In particular: the anti $\nu-e$ appearance from anti-$\nu\mu$ beam in the accelerator LSND [1] experiment; the $\nu-e$ disappearance by SAGE [2] experiment; (observed/predicted rate R = 0.84 ± 0.05); the GALLEX [3] experiment during its calibration with Mega-Curie source; and the anti $\nu-e$ disappearance of near-by Nuclear Reactor [4] experiments (R = 0.934 ± 0.024).
- Awaiting the SBND startup, we are proposing an alternate option for initial data taking to be initiated approximately by the beginning of next year already with the partial ICARUS configuration in place.
- The main goal of this investigation will be the definitive verification with ICARUS of the recent observation of the sterile neutrino oscillation claimed by the NEUTRINO-4 experiment.
- Directly in analogy with NEUTRINO 4, the NuMI beam will allow ICARUS to clarify with high statistics the ν-e cross-sections
- In addition, ICARUS would perform accelerator-based dark matter searches both with BNB and NuMI beams.

The NEUTRINO-4 experiment

- The NEUTRINO-4 reactor experiment has recently presented a new and remarkable result with the first direct experimental observation of neutrino produced oscillations by an additional sterile neutrino, due to disappearance in the positron + neutron channel as a function of L/E, with L the distance travelled (m) and E energy (MeV) of the incoming ν-e.
- With NEUTRINO-4 the hypothesis of oscillation is verified by direct measurements with a movable and spectrum sensitive detector of the anti-neutrino flux and energy spectrum vs. distance near a Reactor core.
- To detect oscillations to a sterile state, one observes a deviation of flux-distance relation from $1/L^2$ dependence and of alterations of the form of energy spectrum with distance.
- This search may be clarified by ICARUS in a few months of data taking, before the completion of the detector upgrade and of the joint operation planned with the SBND detector.

The NEUTRINO-4 data

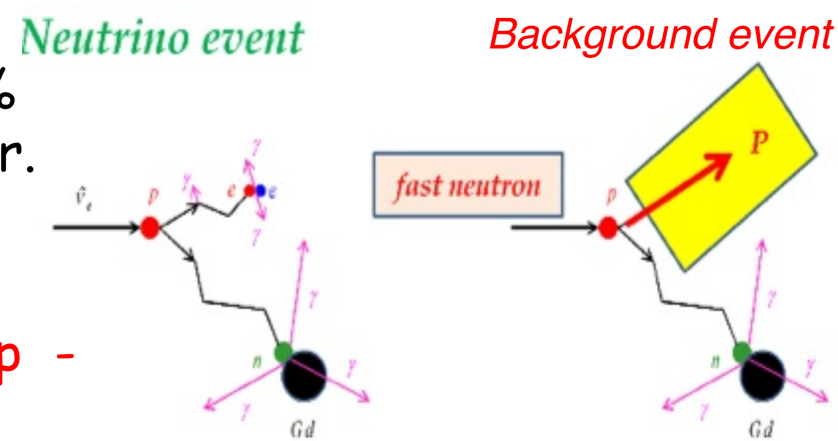
- NEUTRINO-4 is based on a very compact Reactor core of 35 x 42 x 42 cm^3 and 90 MW power. The distance from the core is 5 m and measurements of the anti-neutrino flux are observed in the range of 6 to 12 m.

- At 8 m distance from the Reactor, ~ 300 anti ν-e events/day with 1 m^3 of liquid scintillator are recorded. At a typical 9 m distance from the core, the anti-ν–ε energy is 9 MeV for L/E = 1 and 3.6 MeV for L/E = 2.5. The reaction is fitted as

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \frac{\Delta m_{14}^2[eV^2]L[m]}{E_{\bar{\nu}}[MeV]}\right)$$

where E is anti-ν energy in MeV, L the distance in meters, Δm_{14}^2 is difference in eV^2 between squared masses of electron and sterile νs, θ_{14} the mixing angle between electron and sterile neutrinos.

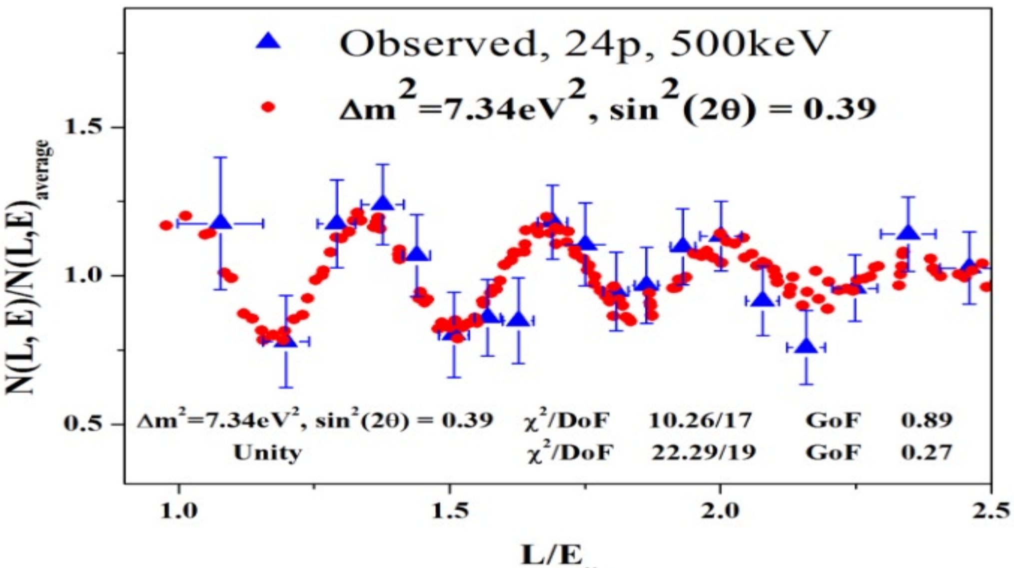
- The anti-νe signal is anti (ν-e) + p -> e+ + n: namely a e+ and a neutron captured by 0.1 % delayed gadolinium added to liquid scintillator.
- Fast ns emitted in interactions of high energy cosmic μs with matter around the detector are the main background with n + p -> p + n with n also captured by gadolinium.



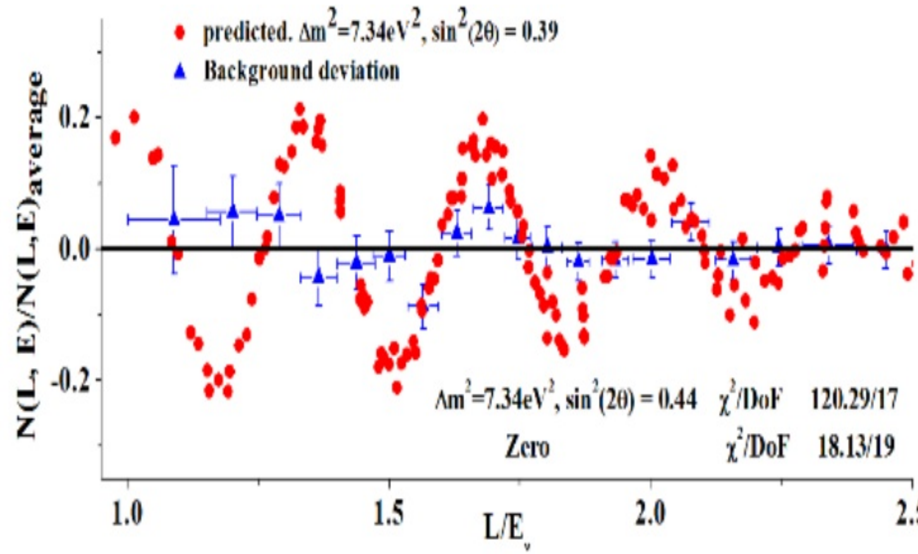
NEUTRINO-4 reactor signals

- Data have been collected for 3 years until June 2019, followed by background measurements until January 2020: 720 days reactor "on" and 417 days reactor "off", with 87 reactor cycles.

Reactor ON



Reactor OFF



- The difference ON-OFF is 223 events per day in the range from 6.5 to 9 meters. The signal/background ratio is 0.54
- The obtained value of the difference between the masses of the electron and sterile neutrinos is $\Delta m_{14}^2 = 7.26 \pm 0.13$ stat ± 1.08 syst => 7.25 ± 1.09 eV^2 and the angle θ_{14} parameter $\sin^2(2\theta_{14}) = 0.26 \pm 0.08$ stat ± 0.05 syst => 0.26 ± 0.09. Lower probability satellite peaks are also observed at other masses.

Comparing $\sin^2(2\theta_{14})$ with other results

- The energy intervals of 500 keV for energy resolution of the detector give $\chi 2/DOF = 17.1/17$ compared with $\chi 2/DOF = 30/19$ without oscillations. The impact is quoted to be 2.8 σ and additional data of NEUTRINO-4 are foreseen to confirm results.

$$\sin^2 2\theta_{14} \approx 0.26 \pm 0.09\ (2.9\sigma)$$

Neutrino-4 experiment

$$\sin^2 2\theta_{14} \approx 0.32 \pm 0.10\ (3.2\sigma)$$

gallium anomaly

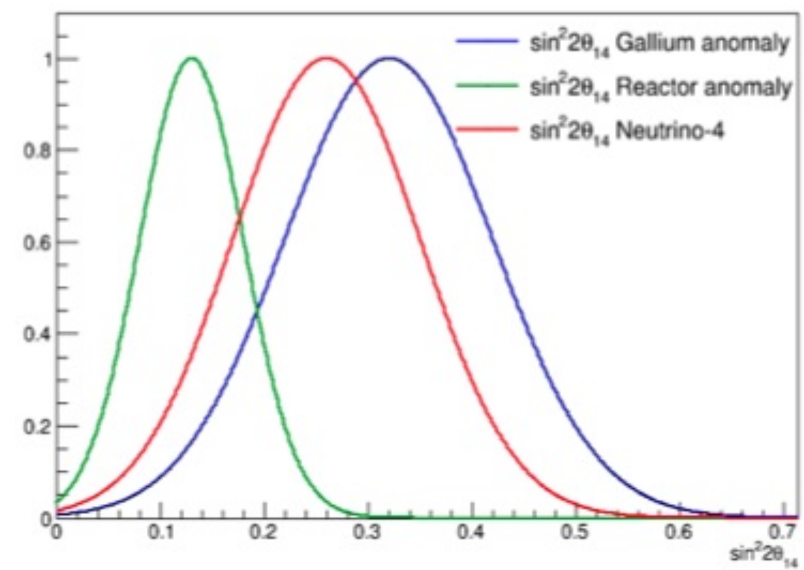
new result is expected from BEST experiment

$$\sin^2 2\theta_{14} \approx 0.13 \pm 0.05\ (2.6\sigma)$$

reactor antineutrino anomaly

Combination of these results gives an estimation for mixing angle

$$\boxed{\sin^2 2\theta_{14} \approx 0.19 \pm 0.04\ (4.6\sigma)}$$



Similarities between NEUTRINO-4 and ICARUS

- ICARUS both at the Booster (1) and at the NUMI (2) has remarkable similarities to NEUTRINO-4 . Therefore ICARUS should be able to settle the NEUTRINO-4 prediction both in the $\nu-\mu$ with the Booster and $\nu-e$ with NUMI.
- The Booster at about 600 m from the target and a short decay path of 50 m can be directly compared to NEUTRINO-4 with a target of 42 cm followed by the detector between 6 and 12 m. The L/E neutrino configurations are therefore closely similar, but with the $\nu-\mu$ collected at ~ 100 times the energy.
- The number of Booster events with the full detector coverage, 1.6 μs spill, 5 10^{12} pot/spill, 5 Hz repetition rate are 12'800 ev/day of which ~7'800 ev/day are due to cosmic rays.

The initial ICARUS programs

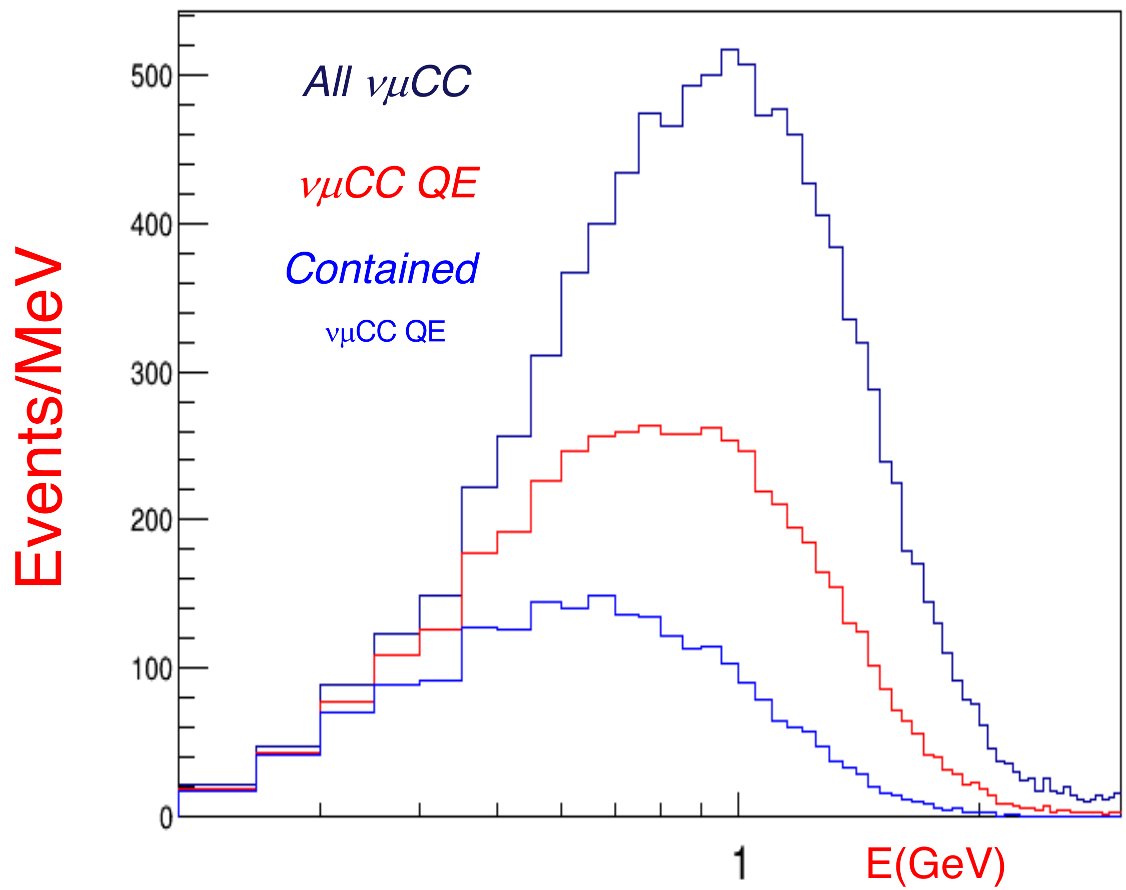
- The early phase of ICARUS data taking will be initiated after the startup of the Fermilab accelerators and primarily dedicated to the following main observations:
  - A.- Detection of $\nu-\mu$ *disappearance* in the Booster beam
  - B.- detection of $\nu-e$ *disappearance* in the NUMI off-axis beam
  - C.- Confirmation of the presence of a a sterile neutrino affecting the *effective masses of the light active neutrin*os
  - D.- Values of $m_{\nu e}^{eff}$ from $|U_{e4}|^2$ as well as of $m_{\nu\mu}^{eff}$ and $m_{\nu\tau}^{eff}$ from $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ can be further compared with direct experiments, f.i. with future KATRIN results
- The comparison between ICARUS at 590 m and SBND at 110 m from the target in the Booster beam to test validity of the 3-1 model and appearance of the ν-e signal will be extended as a subsequent phase for the scheduled duration of the combined run.
- An early confirmation by ICARUS of the NEUTRINO-4 L/E result may widely influence the subsequent programs with SBND.

The ICARUS analysis programs A and B

- The main purpose is the confirmation of the NEUTRINO-4 experiment with ICARUS in the $\nu-\mu$ and ν-e channels.
- Analysis is initiated by the presence within the 1 ms visual signal of all higher ionization stopping tracks confirmed to be due to a proton. The line trajectory is reconstructed backwards from its highest ionization point.
- The other end of the "proton" must be attached either to a "muon" or of a singly ionizing electron departing at an angle.
- The activations of the CRT trigger and of the 3 m concrete shielding do not modify the analysis procedure but only reduce the number of events to be studied.
- The event is reconstructed in 3D views and for contained events.
- The distribution following NEUTRINO-4 of t L/E is plotted with the total energy E of the event and the distance L to the neutrino beam, searching for the presence of sterile neutrino oscillations.

Expected ICARUS Booster rates

- ~560'000 νμ–CC events, corresponding to 6.6×10^{20} pot in 3 years and the ICARUS <u>active</u> volume
- The μCC-QE interactions are ~49% of all charged current events.
- Requiring the event to be contained within the ICARUS active volume guarantees a better reconstruction resulting in ~118'000 collected events .



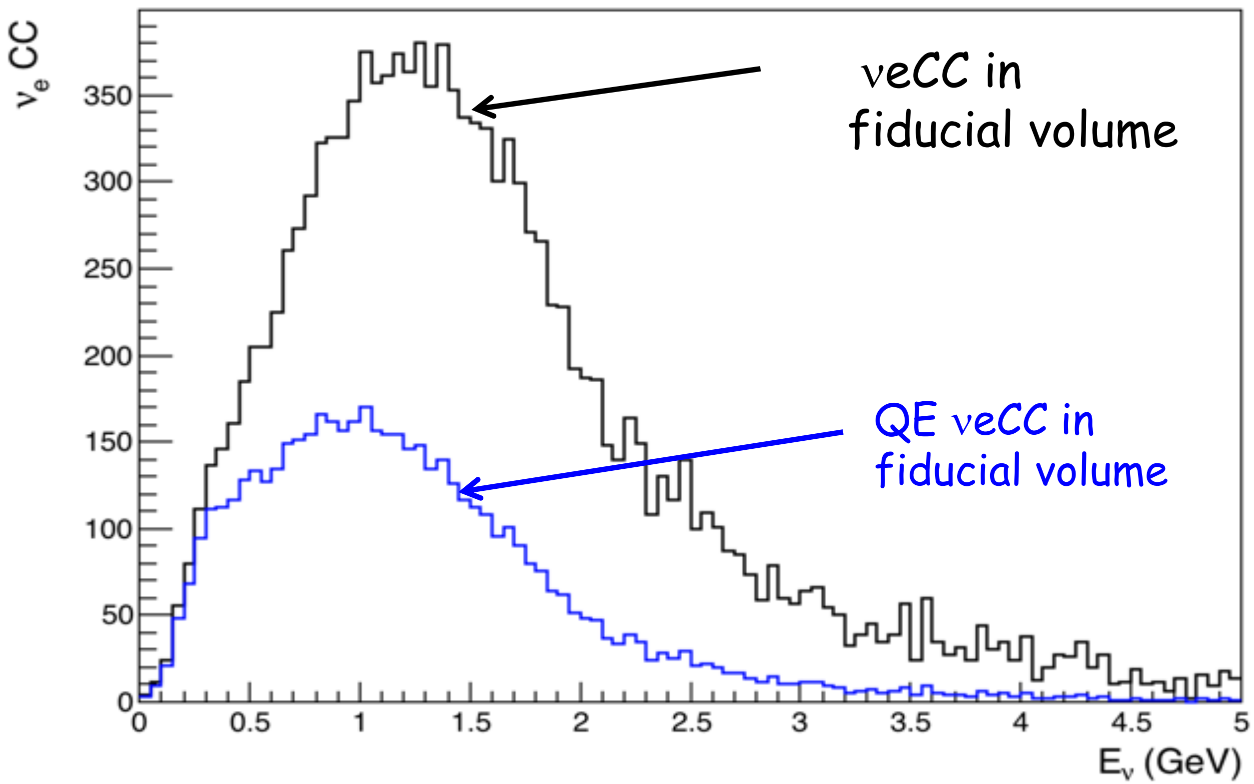
νμCC: ~ 560'000 events
νμCC QE: ~270'000 events
Contained νμCCQE: ~118'000 events
(~ 350 beam ev/day)

Expected NUMI rates

- The NUMI off-axis proton beam is located at ~ 700 m from ICARUS and at an off-axis angle of 6 degrees. One year with 0.75 Hz NUMI repetition rate and spills of 6×10^{13} ppp corresponds to a 6×10^{20} pot exposure. For positive (negative) focussing we expect 4.3×10^5 *CC* events/y (~3.7×10^5 *CC* evs/y).
- The ratio (ν-e *CC*)/(ν-μ *CC*) = 4.8 % for positive focusing and about 40% are quasi-elastic (QE).
- NUMI rates correspond to one *CC* event each 23 spills for positive focussing (one *CC* event each 26 spills in negative focussing).
- Although the $\nu-\mu$ from NUMI can also be analysed, kaons are primary goal in the off-axis NUMI, leading to a much larger participation of the $\nu-e$ signal and with a neutrino energy distribution similar to the Booster beam case.

NuMI νeCC QE in one beam-year

- In the active volume 20600 νeCC are expected in one year (6×10^{20} pot) by NuMI, of which ~40% are quasi elastic.
- ~5200 νeCC QE almost fully contained are expected in one year in a suitable fiducial volume, selected by excluding 25 cm from the lateral TPC walls, 30 cm (50 cm) from the upstream (downstream) wall.



Comparing triggers inside and outside the burst

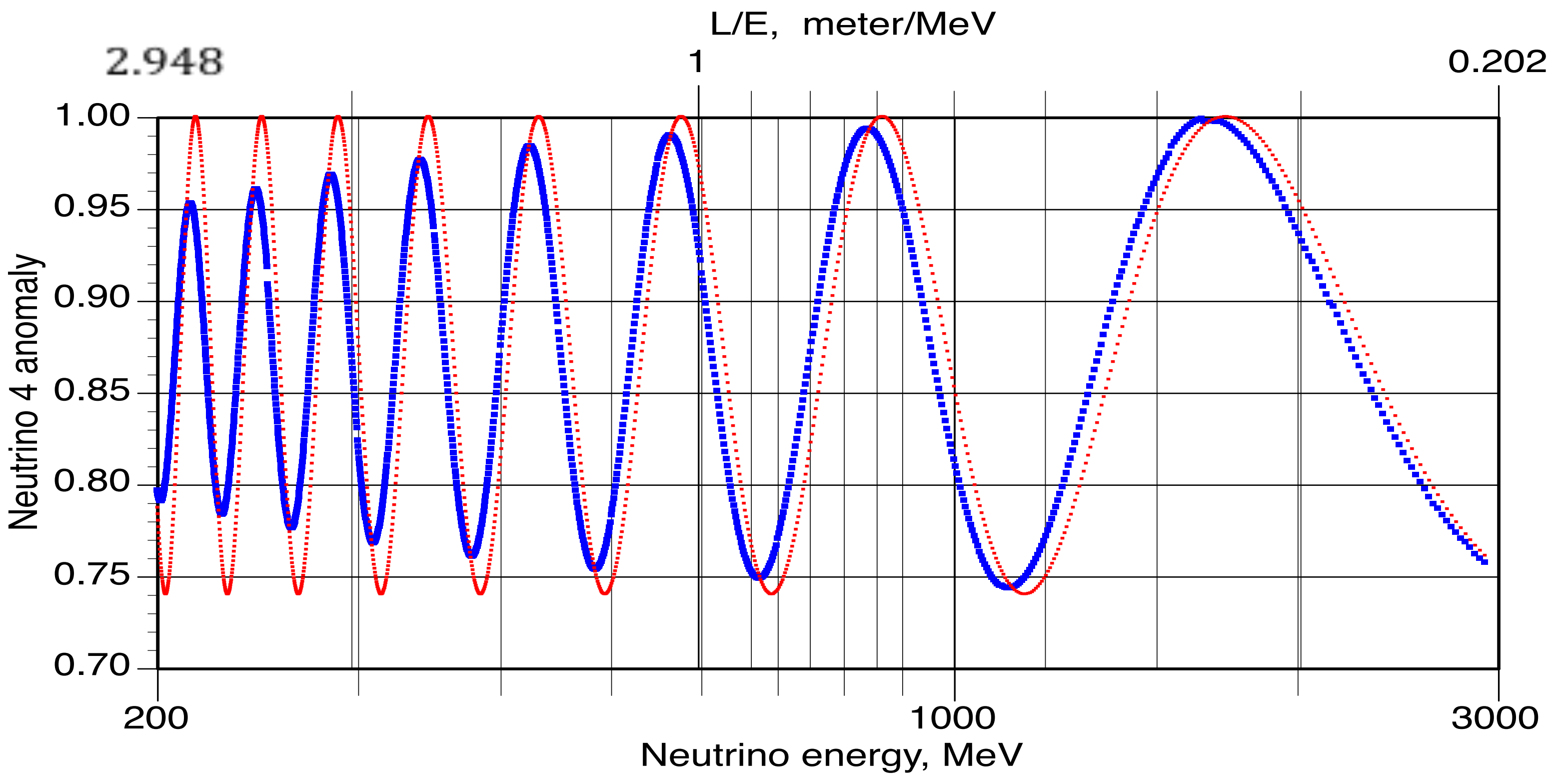
- The full burst duration is 1.6 μs for the Booster and 9.5 μs for NUMI. The further possibility to limit the phase angular excursion of the RF may be applied, reducing its effective active length. If it equals to 1/5, this will reduce the actual Booster burst length to 0.3 μs.

- Inside the bursts (beam ON), in analogy with NEUTRINO-4, the signal will be searched for the experimental observation of neutrino produced oscillations due to the disappearance in the $\nu-\mu$ and $\nu-e$ channels as a function of L/E, where L is the distance travelled (m) of the incoming $\nu-\mu$ (MeV) and E the energy for the Booster and of the corresponding values but with incoming $\nu-e$ for the NUMI configuration.

- Outside the bursts (beam OFF), the trigger rate will be dominated by the cosmic ray background. The images of the full 1 ms long visual events will be extracted to demonstrate the absence of an instrumental NEUTRINO-4 like signal.

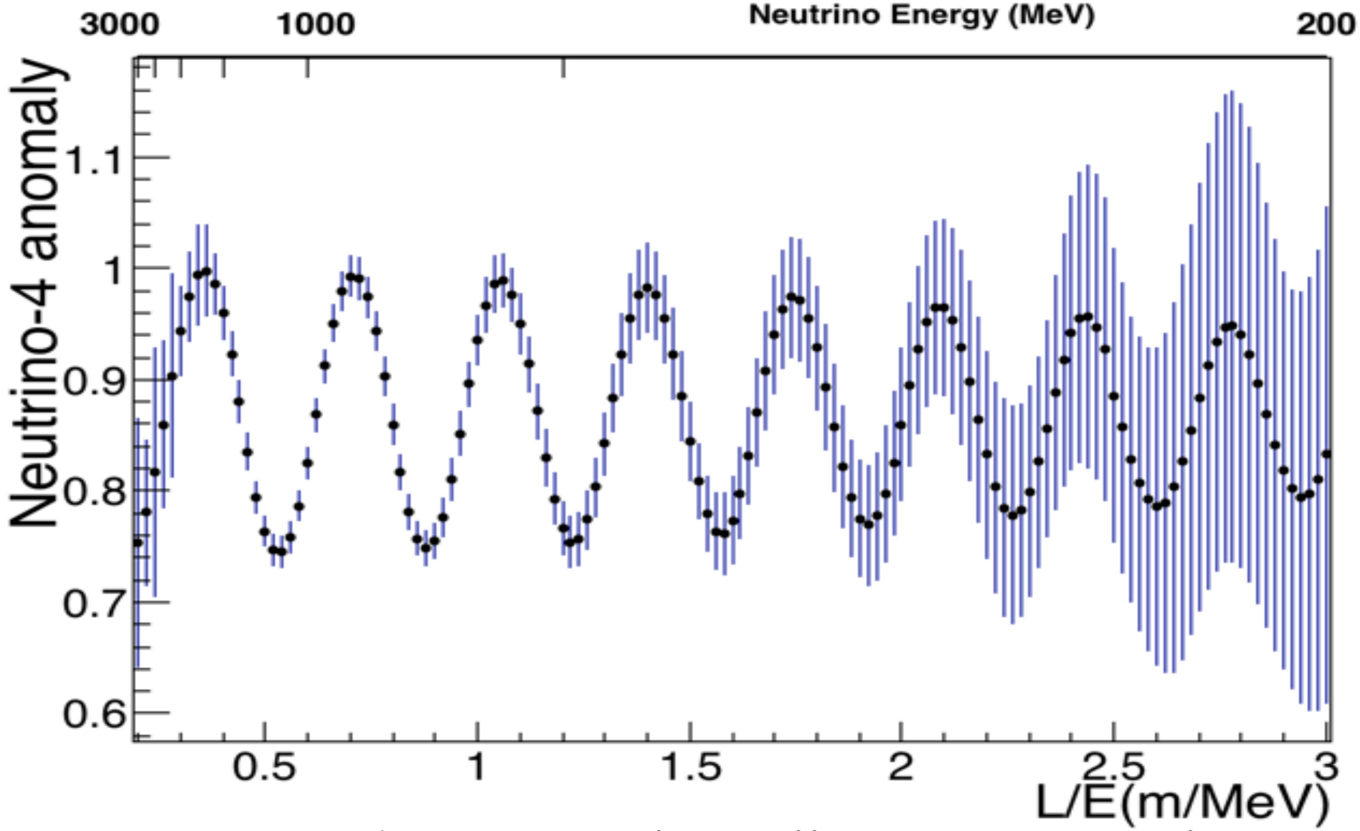
ICARUS prediction for NEUTRINO-4

- The expected Neutrino-4 muon disappearance signal is shown for ICARUS as a function of neutrino energy E in MeV (below) and L/E in meters/MeV (above).



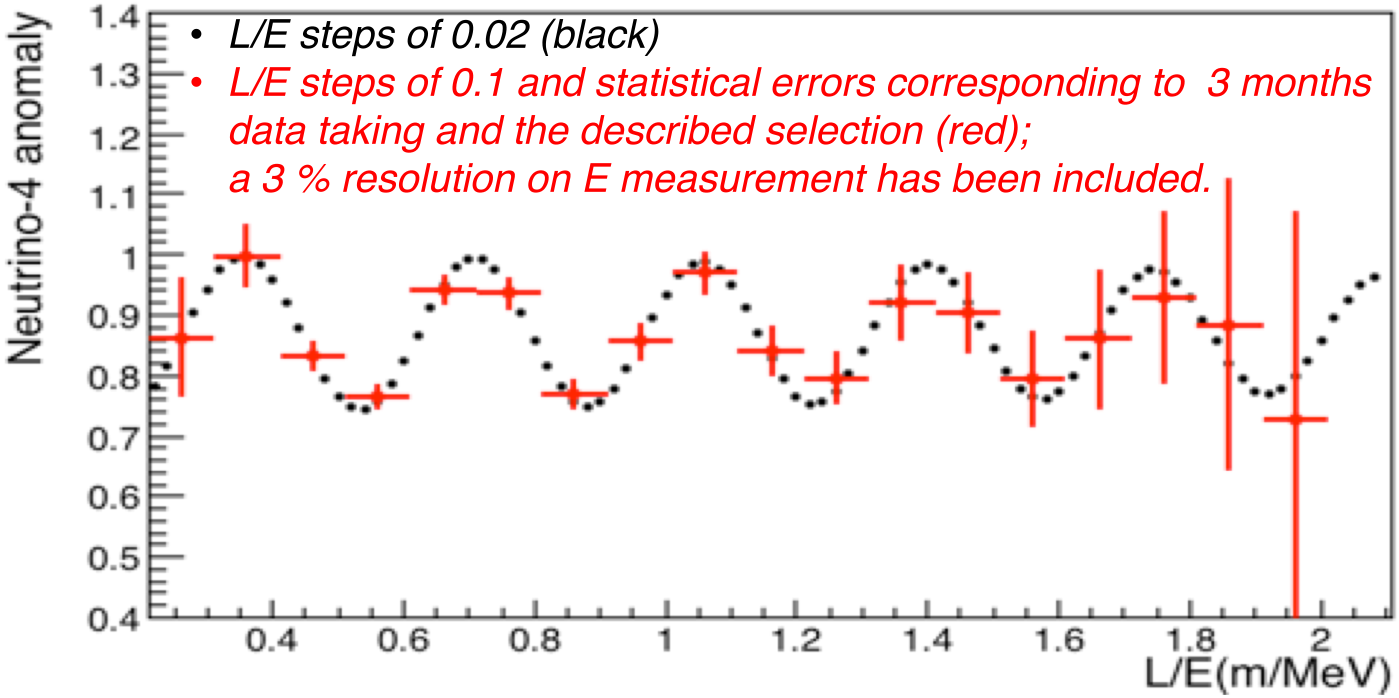
- The blue line is the anomaly for the L averaged position accounting for the actual distribution of the ν travel distance while the red curve is the peak value at the center position.

Booster after 3 years and for NEUTRINO-4 prediction



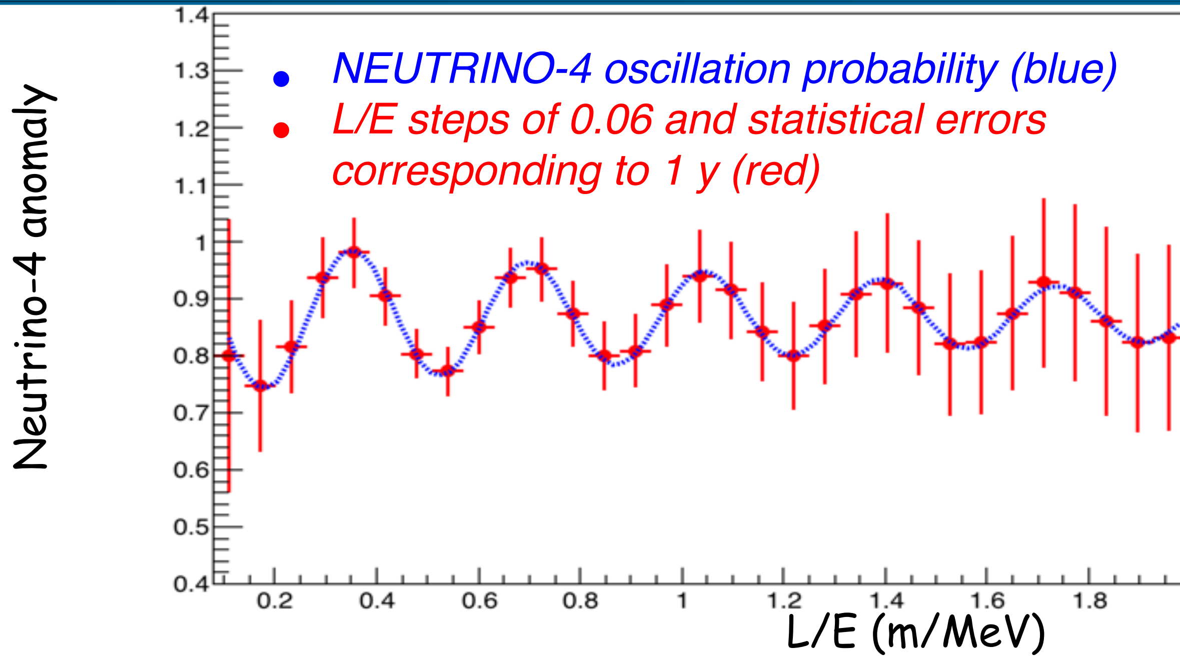
- The figure represents the survival oscillation probability in the presence of the Neutrino-4 anomaly.
- The calculation has been performed considering a 3 years long run (~117k $\nu\mu$CC QE contained events) for steps of delta(L/E) = 0.02 and considering the best fit of NEUTRINO-4 parameters Δm^2_{N4}=7.25 eV^2 and $\sin^2 2\theta_{N4}$=0.26 (only statistical errors are reported).

Results in 3 months, adding $L\mu > 50$ cm & expected energy resolution



- The performed study on the trigger shows a total reduction of ~3% on $\nu\mu$CC QE contained events concentrated at low $E\nu$ increasing the statistical uncertainty at high L/E values.
- Additional request on the muon length $L\mu > 50$ cm for a better μ identification has been also included resulting in ~11500 events in 3 months data taking.
- As a first approximation ~3% smearing on E has been applied (a resolution better than 1% is expected for μs which take ~70% of the ν energy).
  As shown in the plot, the oscillation pattern is not spoiled when the precision on reconstructed $E\nu$ for contained $\nu\mu$CC QE events is accounted for.

Result after 1 year in NuMI and for NEUTRINO-4 prediction



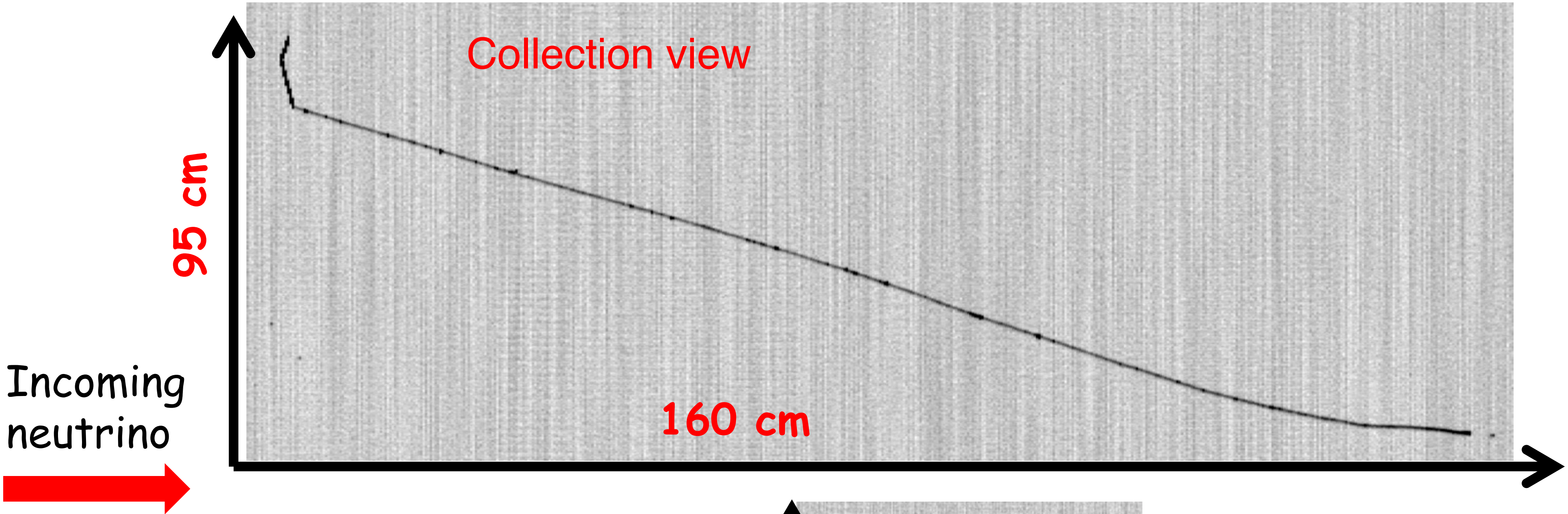
- The survival oscillation probability in the presence of the Neutrino-4 anomaly is shown considering a 1 year data taking (~5200 νeCC QE) for the best fit of NEUTRINO-4 parameters $\Delta m^2_{N4}=7.25\ eV^2$ and $\sin^2 2\theta_{N4}=0.26$. Only statistical errors are reported, effects of energy reconstruction are expected marginal, given the optimal ICARUS energy resolution for e- and e.m. showers.
- Despite the 725 m long NuMI decay tunnel most of νe are produced by kaons decaying close to target. The residual variations of the distance travelled by νs do not wash out the characteristic Neutrino-4 oscillatory pattern.

The procedure for the initial ICARUS data

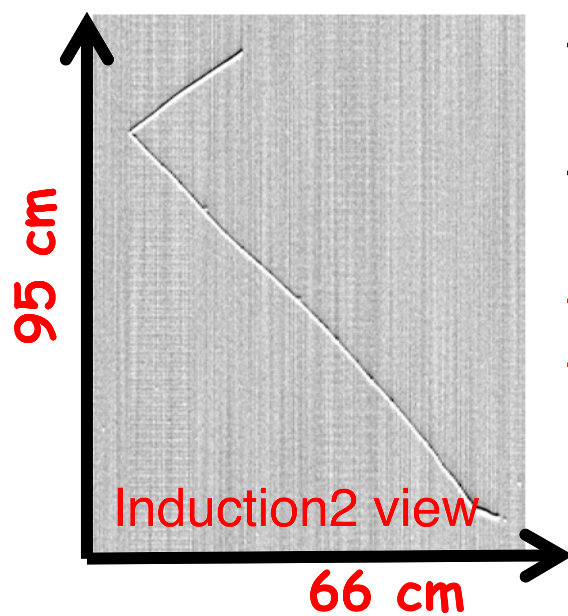
- The proposed early search will be limited to observation of CC QE processes $\nu-\mu + n \rightarrow \mu + p$ for Booster and $\nu-e + n \rightarrow e^- + p$ for NUMI.
- Only events with one well separated sizeable PMT's fast signal in coincidence with beam spill will be retained. Initial, automatic event selection is based on:
  - (1) a sum of signals from the PMT 's above a threshold and
  - (2) the absence of signals from the CRT over its 4π surface, occurring a few ns after or before the earliest of the PMT signals within the event.
- This simple fast signal selection will reduce of ~one order of magnitude the events initially in excess of 10000/day. Next the 3-D 1 ms long image will be displayed only for these resulting triggers.
- All connected vertices of two joining tracks will be searched inside the 1 ms image — one for a high dE/dx stopping proton and the other either for a stopping μ (for Booster) or a single e-showering (for NUMI).
  All other tracks in the 3-D 1 ms long image will not be considered.
- The kinematics of finally recorded vertices will be compared with predictions of NEUTRINO-4 experiment,
- The absence of these events for a test sample of out of beam-time recorded events is required.

MC event Event 14

- A low energy q.e. $\nu\mu$CC event p + μ.



Eν = 0.74 GeV   Edep = 0.61 GeV



T_μ = 0.4 GeV
R_μ = 166 cm
T_p = 0.2 GeV
R_p = 25 cm
T_p/R_p =8 MeV/cm
T_μ/R_μ = 2.4 MeV/cm

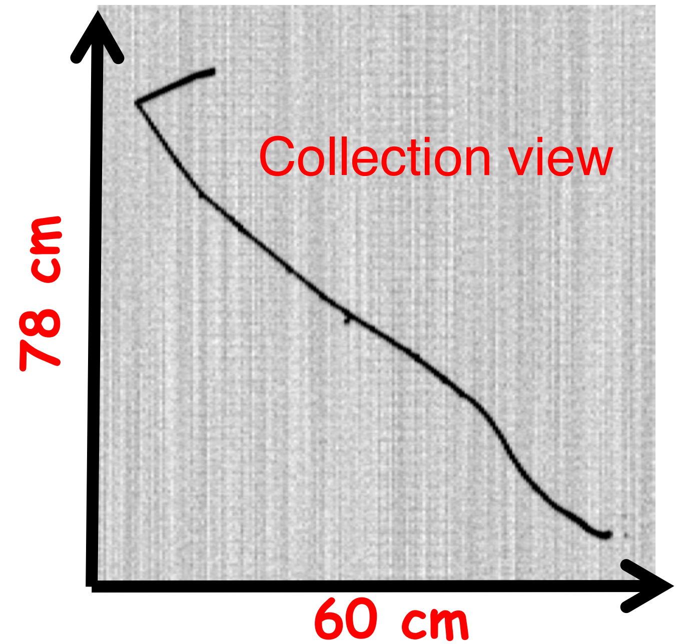
To obtain the total neutrino energy we should include to the Edep the mass of the muon

MC event Event 14

- A low energy q.e. $\nu\mu$CC event p + μ.

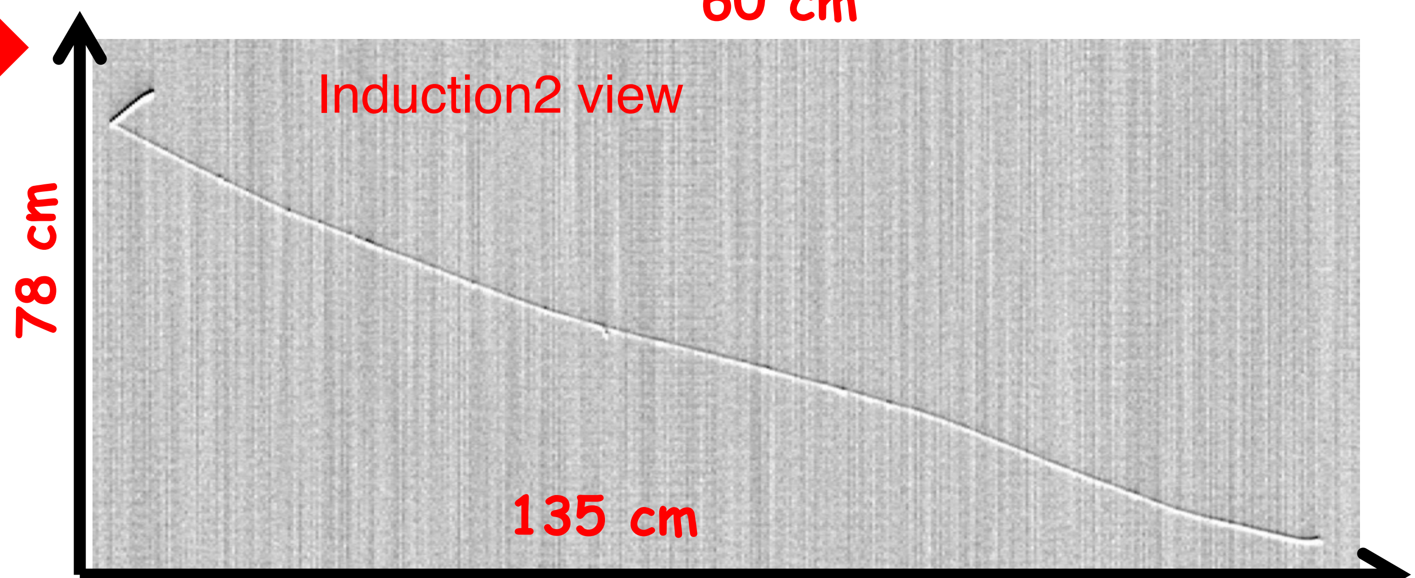
$E\nu$ = 0.6 GeV
Edep = 0.47 GeV

T_μ = 0.35 GeV
R_μ = 144 cm
T_p = 0.11 GeV
R_p = 9.4 cm
T_p/R_p = 12 MeV/cm
T_μ/R_μ = 2.4 MeV/cm



To obtain the total neutrino energy one should include to Edep the muon mass

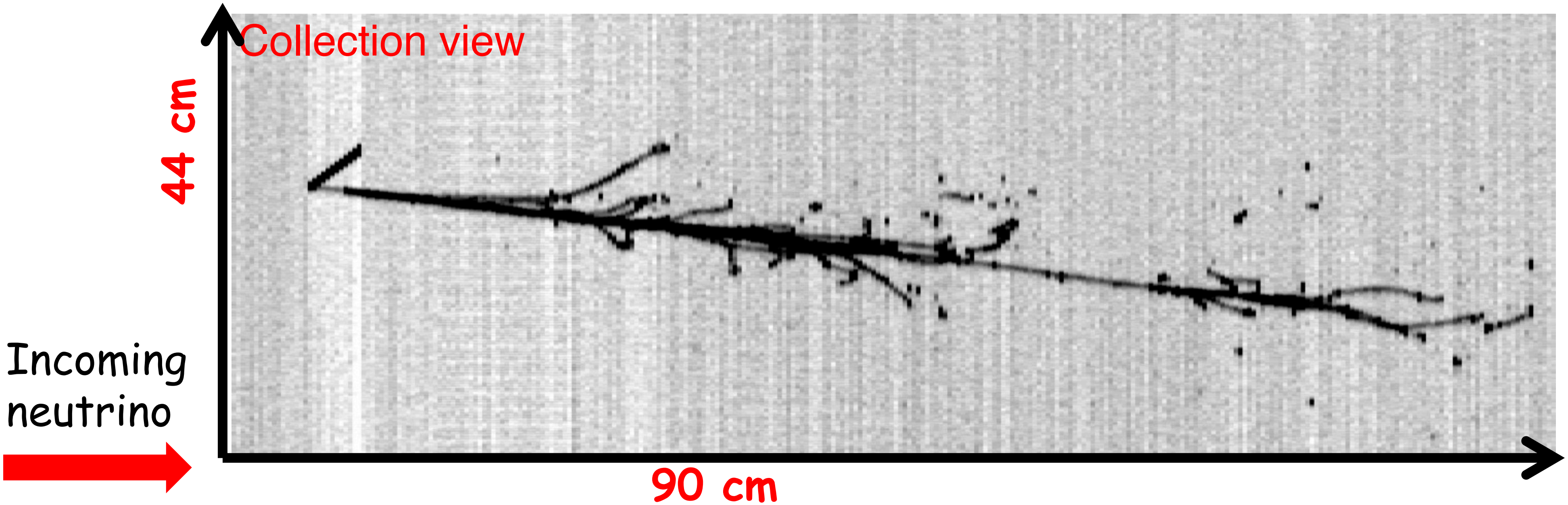
Incoming neutrino



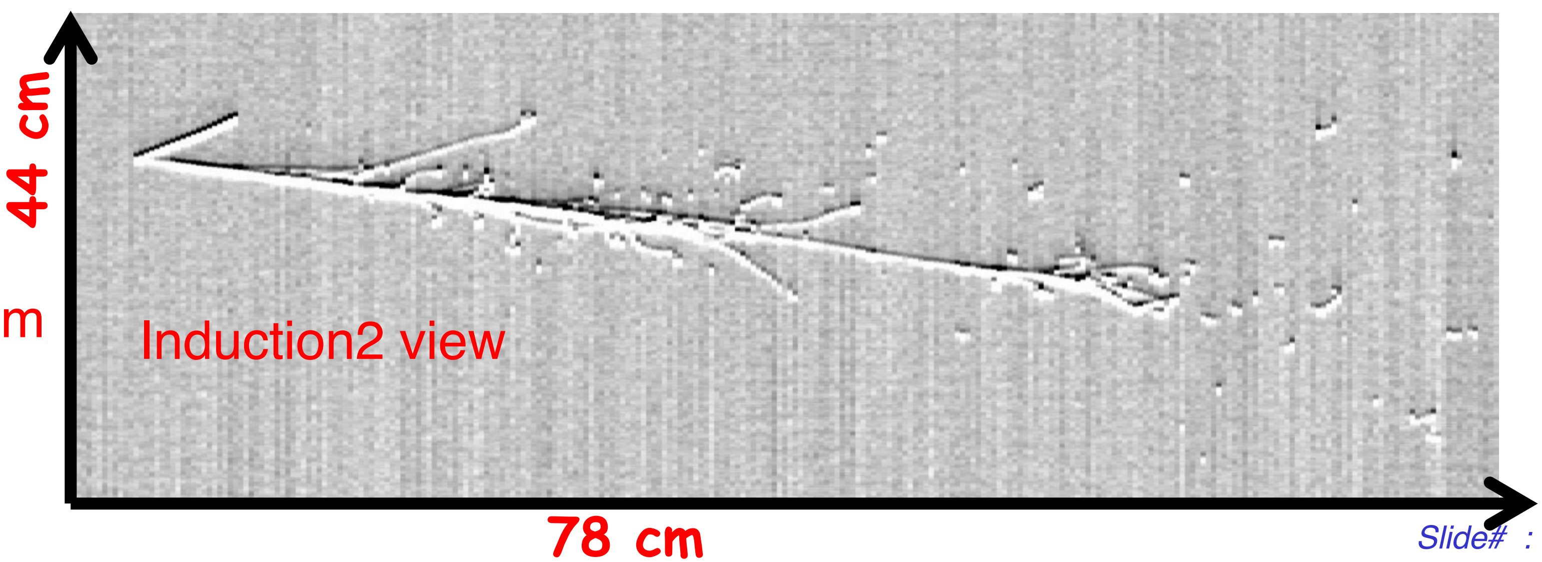
MC event Run 5 SubRun 44 Event 64

- A clear q.e. νe event: p + e.

Eν = 1.34 GeV Edep = 1.29 GeV



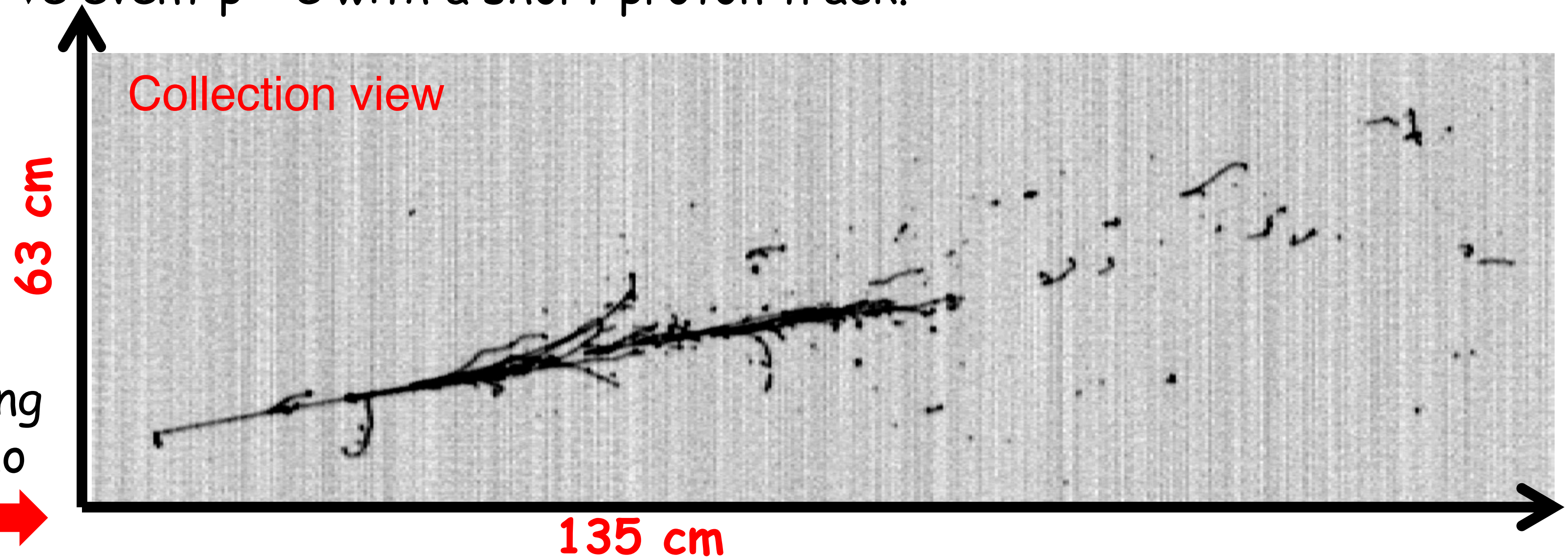
E_e = 1.21GeV
T_p = 93 MeV
R_p = 7cm
T_p/R_p = 13.2 MeV/cm



MC event Run 5 SubRun 47 Event 63

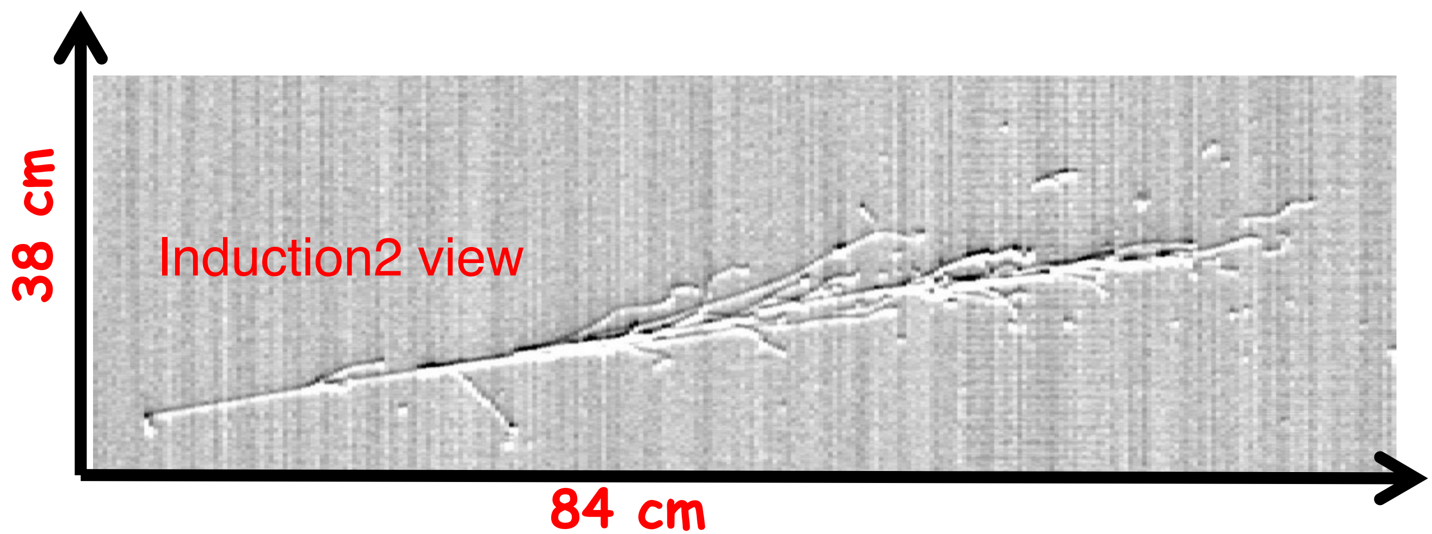
- A q.e. νe event p + e with a short proton track.

Incoming neutrino



$E\nu$ = 1.6 GeV E_{dep} = 1.57 GeV

E_e = 1.54 GeV
T_p = 40 MeV
R_p = 1.6 cm
T_p/R_p = 25 MeV/cm



The ICARUS analysis program C: The sterile neutrino

- Cosmology and only three neutrinos would give a very small value for the sum of neutrino masses.
- However a fraction of the effective sterile mass m_s is then mixed in the effective masses of the light neutrinos.
- Quite independently from the outcome of the NEUTRINO-4 experiment, there is a very solid information about the possible existence of one sterile neutrino m_4, that ICARUS may be able to observe with L/E over a wide mass range, provided m_1^2, m_2^2, $m_3^2 \ll m_4^2$. $|U_{e4}| = \frac{1}{4}\sin^2(2\theta_{14})$.
- Both $m_{\nu\mu}{}^{eff}$, and $m_{\nu e}{}^{eff}$ masses may be estimated:
  $m_{\nu e}{}^{eff} \approx \mathit{sqrt}\,(m_4^2|U_{e4}|^2) \approx \frac{1}{2}\,\mathit{sqrt}\,(m_4^2 \sin^2(2\theta_{14}))$ and
  $m_{\nu\mu}{}^{eff} \approx \mathit{sqrt}\,(m_4^2|U_{m4}|^2)$.

ICARUS analysis program C Predicting the ν–e mass

COMPARISON WITH EXPERIMENT KATRIN ON MEASUREMENT OF NEUTRINO MASS

$$m_{\nu_e}^{eff} = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

$$\Delta m_{14}^2 \approx m_4^2, \ldots |U_{14}^2| \ll 1$$

Limitations on the sum of mass of active neutrinos $\Sigma m_\nu = m_1 + m_2 + m_3$

from cosmology are in the range 0.54 ÷ 0.11eV

$$m_{\nu_e}^{eff} \approx \sqrt{m_4^2 |U_{e4}|^2} \approx \frac{1}{2}\sqrt{m_4^2 \sin^2 2\theta_{14}} \leftarrow m_1^2, m_2^2, m_3^2 \quad m_4^2$$

$$\boxed{m_4 = (2.68 \pm 0.13)\text{eV}}$$

$$\sin^2 2\theta_{14} = 4|U_{14}|^2(1 - |U_{14}|^2)$$

$$\sin^2 2\theta_{14} \approx 0.19 \pm 0.04(4.6\sigma)$$

$$|U_{14}^2| \approx \frac{1}{4}\sin^2 2\theta_{14}$$

$$\boxed{m_{\nu_e}^{eff} = (0.58 \pm 0.09)\text{eV}}$$

NEUTRINO -4 RESULTS

$m_{\nu_e}^{eff} \leq 1.1$ eV (CL 90%)

KATRIN Collaboration. M. Aker et al., Phys. Rev. Lett. 123, 221802 (2019). arXiv:1909.06048

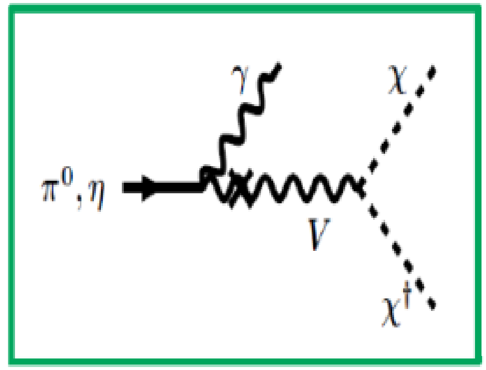
ICARUS analysis program D: other measurements

- The value $m_{\nu e}^{eff}$ = (0.58 ± 0.09) eV has been derived from the m_4^2 prediction of NEUTRINO-4 and it does not contradict the upper direct limit of neutrino mass $m_{\nu e}^{eff} \leq 1.1$ eV (CL 90%) of KATRIN.
- Direct measurements on the values of $m_{\nu e}^{eff}$ from $|U_{e4}|^2$ as well as of m_{nm}^{eff} and $m_{\nu t}^{eff}$ from $|U_{m4}|^2$ and $|U_{t4}|^2$ can be further compared in several other experiments

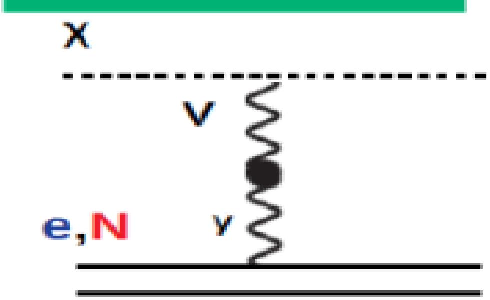
Dark Matter Search @ICARUS using NuMI

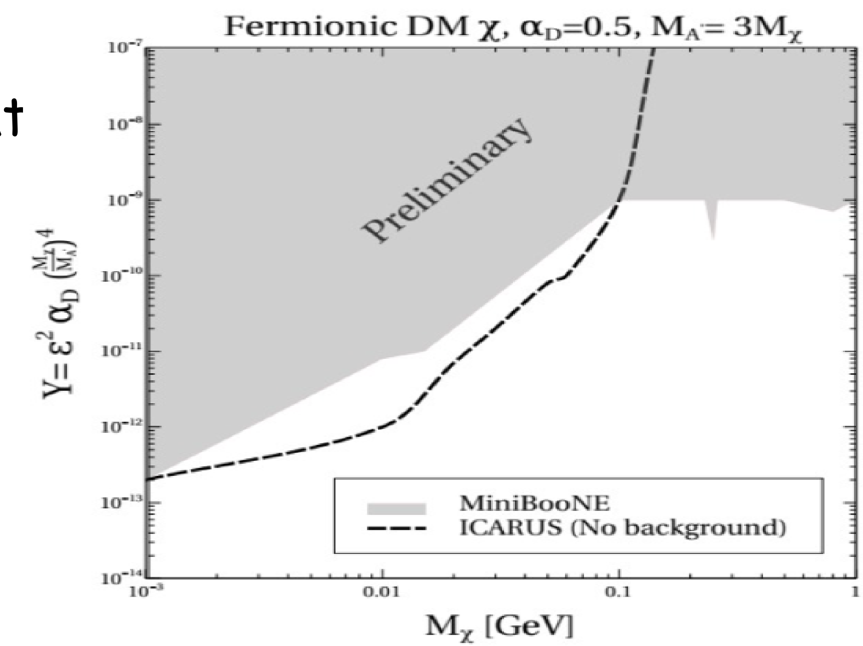
- Models of sub-GeV dark matter typically involve scalar or fermion, Dark Matter (DM) "mixes" with Standard Model through vector or scalar mediators (Vector Portal/Higgs Portal);
- DM Production: via neutral hadrons;
- DM Detection: DM-electron scattering - use angle cut for selecting the very forward outgoing electron;
- Background: Any standard process with a final state electron;
- The searched DM events will be searched using 120 GeV NuMI Beam with 1021 pot stat
- Preliminary sensitivity looks promising: years of data can allow to explore a large range of Dark Matter model parameters
- Detector simulation of signal/background in progress.
- Design of trigger for signal selection in progress.

Meson decay



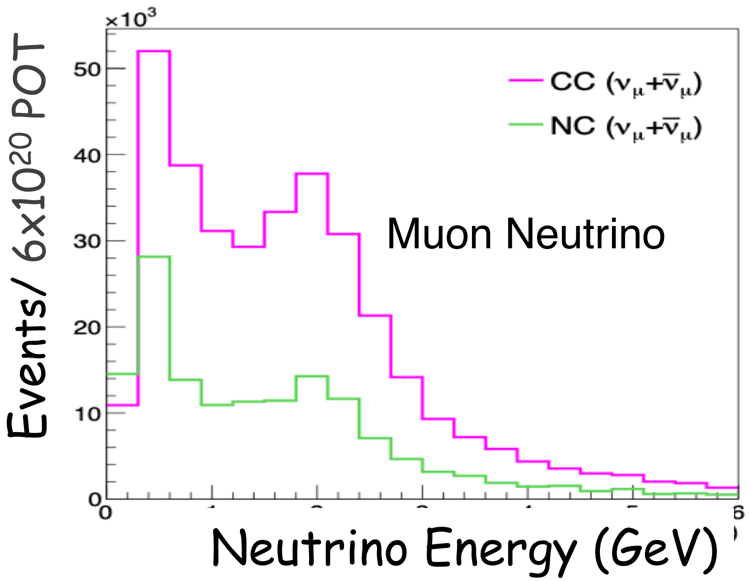
Elastic scattering

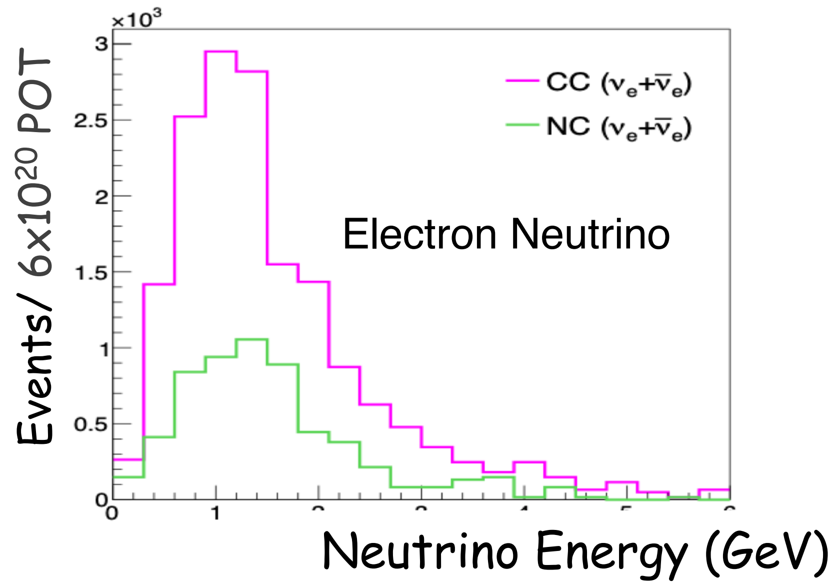




Neutrino Interactions from NuMI off axis

- Predicted events per year (6×10^{20} POT) in ICARUS LArTPC active volume
  - CC muon neutrino = 4.3×10^5, NC muon neutrino = 1.9×10^5
  - CC electron neutrino = 2.0×10^4, NC electron neutrino = 7.3×10^3





- Electron neutrino and muon neutrino event selection studies in progress:
  - Investigating cosmic background rejection using TPC, PMT and CRT;
  - Using constrained flux simulation from the MINERvA experiment to understand the neutrino flux.


Thank you !

Backup

Conclusions

- To conclude, the early phase of ICARUS data taking will be initiated after the startup of the Fermilab accelerators and primarily dedicated to the following main observations:
  - A.- Detection of $\nu-\mu$ *disappearance* in the Booster beam
  - B.- detection of $\nu-e$ *disappearance* in the NUMI off-axis beam
  - C.- Confirmation of the presence of a a sterile neutrino affecting the *effective masses of the light active neutrinos*
  - D.- Values of $m_{\nu e}^{eff}$ from $|U_{e4}|^2$ as well as of $m_{\nu\mu}^{eff}$ and $m_{\nu\tau}^{eff}$ from $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ can be further compared with direct experiments, f.i. with future KATRIN results
- The comparison between ICARUS at 590 m and SBND at 110 m from the target in the Booster beam to test validity of the 3-1 model and appearance of the ν-e signal will be extended as a subsequent phase for the scheduled duration of the combined run.
- An early confirmation by ICARUS of the NEUTRINO-4 L/E result may widely influence the subsequent programs with SBND.